TECHNICAL RESPONSE

FISHERIES

Response to Comment on "Tracking the global footprint of fisheries"

David A. Kroodsma[1]*, Juan Mayorga[2,3], Timothy Hochberg[1], Nathan A. Miller[4], Kristina Boerder[5], Francesco Ferretti[6], Alex Wilson[7], Bjorn Bergman[4], Timothy D. White[6], Barbara A. Block[6], Paul Woods[1], Brian Sullivan[7], Christopher Costello[2], Boris Worm[5]

Amoroso *et al*. demonstrate the power of our data by estimating the high-resolution trawling footprint on seafloor habitat. Yet we argue that a coarser grid is required to understand full ecosystem impacts. Vessel tracking data allow us to estimate the footprint of human activities across a variety of scales, and the proper scale depends on the specific impact being investigated.

We welcome Amoroso *et al.*'s comment (*1*), which demonstrates the power of vessel tracking data to estimate the environmental footprint of human activities on ocean ecosystems over a range of relevant scales. Their contribution also highlights the importance of making vessel tracking data freely available, allowing others to ask more detailed questions about the effects of fishing on ocean ecosystems. We disagree, though, that the environmental impacts of fishing can be easily divided into "diffuse" and "direct," or that there is a "correct" scale of analysis; rather, the chosen scale depends both on the method of fishing and the question being asked. We further demonstrate that our estimate of the area of the ocean fished was conservative given the questions we addressed.

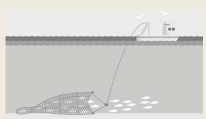
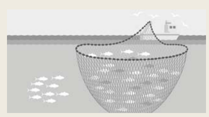
Consider the analogous challenge of calculating the global environmental footprint of motor vehicles from car tracking data. To estimate the immediate habitat loss, one would measure the area covered by roads (1- to 100-m scale). If the question pertained to air quality, the scale of inquiry would broaden to a range of 100 m to 100 km from the roadside (*2*). Ecosystem impacts manifest at various scales (1 to 100 km), such as through roadkill and fragmentation (*3*), whereas climate impacts are global (>1000 km); hence, the scale of analysis depends on the environmental damages in question. The determination of which impacts are diffuse versus direct is subjective; for example, a person with asthma would deem air pollution to be a direct impact.

In fisheries, disturbance of seafloor habitat by bottom trawling is one of the best-known environmental aspects of bottom fishing (*4*). Better estimates of this footprint, as shown by the analyses of Amoroso *et al.*, can now be achieved using fine-scale automatic identification system (AIS) vessel tracking data. But this scale of analysis is not universally applicable. Drifting longlines or purse seines, although they traverse more of the ocean than trawlers, have no contact with the seafloor, and thus no footprint by this assessment. Industrial longlines, for example, contain thousands of baited hooks and move with the local currents. A single set can "drift" many kilometers, intersecting the paths of mobile predators such as tuna and sharks along the way. Thus, the footprint of drifting longlines would be the area of the polygon defined by the start and end locations of the setting and hauling of gear (mean for a study of the Hawaii longline fleet: 224 km^2) (*5*). For tuna purse seines, it would be the area of the net, which can be almost half a kilometer in diameter (*6*) (Table 1).

A broader question relates to the spatial footprint of fishing on the abundance of target species. Catching fish in one location likely affects biomass across roughly the area that those fish travel. A review of commonly targeted species shows wide ranges for different species. Tagging data of European hake, which is one of the top species caught by trawling in southern Europe, show that individuals generally travel 20 to 40 km over several months, with some traveling more than 200 km (*7*). In the Bering Sea, Pacific cod and sablefish are two of the three most frequently landed target species by trawlers. Pacific cod were recaptured typically 20 to 370 km from where they were released, with some traveling more than 900 km (*8*), and sablefish were found to travel at a mean rate of 191 km/year (*9*). Many pelagic species travel much farther. In the Pacific, the top species targeted by longlines and purse seines are yellowfin, bigeye, skipjack, and albacore tuna. Tagging data show that all of these species travel hundreds to thousands of kilometers (*10*), and the average "activity space" of yellowfin tuna exceeds 250,000 km^2, the area of a grid cell just under 5° × 5° at the equator (*11*). All of these fish travel distances much larger than 0.01° (~1.1 km), and almost all are larger than 0.5° (~55 km). Figure 1 illustrates these much larger grid sizes that reflect typical species movements and compares them with the highest resolution of our public dataset.

The footprint calculation in our paper (*12*) served two goals: (i) to compare our dataset with previous global fisheries datasets, which are gridded at the same 0.5° scale (*13*, *14*); and (ii) to make a general comparison with the area used for other forms of food production, namely agriculture. The majority of agricultural land is used for grazing (*15*), and the footprint of this

Table 1. Appropriate scales for different footprints. Examples of appropriate scales for calculating the footprint of fishing, given different fishing gear (columns) and questions asked (rows).

	 **Bottom trawl targeting European hake in the Adriatic Sea**	 **Drifting longline targeting yellowfin tuna in the Pacific**	 **Purse seine targeting yellowfin tuna in the Pacific**
Seabed disturbed by gear	25–30 m (width of door spread of trawl in Adriatic) (*16*) × vessel track while fishing	0	0
Area swept by gear while fishing	25–30 m (width of door spread of trawl in Adriatic) × vessel track while fishing	Per set, length of longline × soak time × mean current (~224 km^2 for study of Hawaii longline fleet) (*5*)	~0.3 km^2 per set (assuming net length ~2 km) (*6*)
Typical movements of target species	~25 km	~500 km	~500 km

[1]Global Fishing Watch, Washington, DC 20036, USA. [2]University of California, Santa Barbara, CA 93106, USA. [3]Pristine Seas, National Geographic Society, Washington, DC 20036, USA. [4]SkyTruth, Shepherdstown, WV 25443, USA. [5]Biology Department, Dalhousie University, Halifax, NS B3H 4R2, Canada. [6]Biology Department, Stanford University, Stanford, CA 94305, USA. [7]Google, Mountain View, CA 94043, USA.
*Corresponding author. Email: david@globalfishingwatch.org

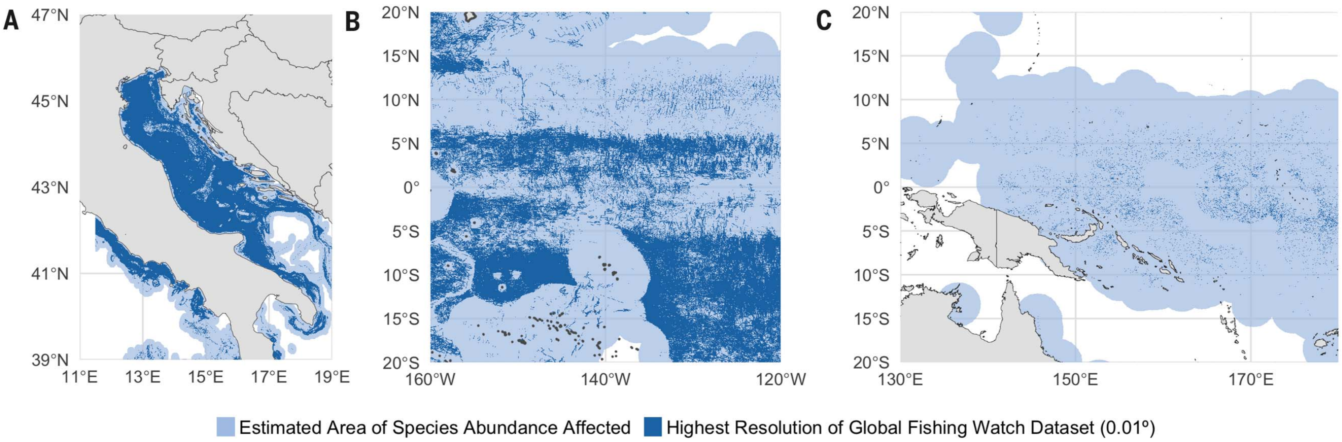


Fig. 1. Area swept by different fishing gear and area of fish biomass affected. Shown is fishing effort in 2016 from AIS data (*11*) for (**A**) trawlers in the Adriatic Sea, (**B**) drifting longlines in the central equatorial Pacific, and (**C**) purse seines in the western equatorial Pacific. Dark blue shows the highest resolution of the dataset, 0.01° resolution (~1.1 km at the equator), which may be a slight underestimate of area swept by drifting longlines and an overestimate of area swept by trawlers and purse seines (Table 1). Light blue shows target species' average movements mapped beyond fishing locations, using the range of European hake in the Adriatic (~25 km) and yellowfin tuna in the Pacific (~500 km).

food production system relates to the area that is grazed, not the area traversed by trucks hauling livestock to slaughter. In other words, the footprint of agriculture relates to the approximate area of ecosystems where a substantial portion of the net primary productivity is appropriated, directly or indirectly, for human consumption. In the ocean, the comparable "area fished" would be the area of the ecosystem that supports targeted fish, not the area swept by fishing gear. Our grid size, about 55 km on a side (0.5° at the equator), is conservative for most commonly targeted species (*8*–*15*). Using this scale, the area of marine ecosystems supporting fish caught by humans is more than four times that of terrestrial ecosystems in agriculture.

Our estimates and those of Amoroso *et al.* are just two of several footprint estimates that can be derived from our AIS vessel tracking data. For example, we can use engine power estimates to infer the fuel used and thus the carbon footprint of vessels in the database. We can also look at the spatial overlap of fishing behavior with different species to understand risks of bycatch. With high temporal resolution, we can estimate how fishing pressure changes across and between years.

It is important to have these vessel tracking data freely available for such analyses, and we hope that other forms of tracking data, like those derived from vessel monitoring systems (VMS), are made more widely available for comparative scientific research. As demonstrated by both Amoroso *et al.*'s analyses and ours, these data can allow us to answer specific questions about the environmental impact of fishing on marine ecosystems, which in turn can contribute to improved, evidence-based management of the oceans.

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